Charm Mixing and *CP* Violation at BaBar

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On behalf of the
BaBar Collaboration

CKM 2012

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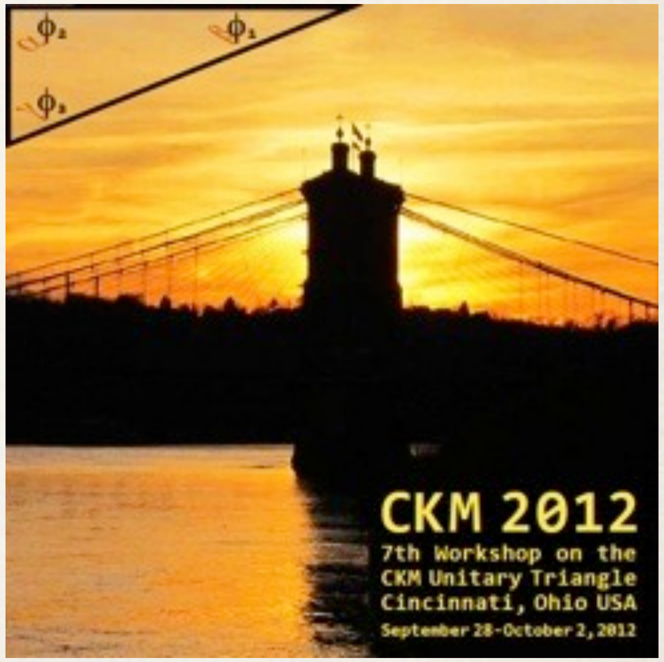


September 30th, 2012

Outline

- Mixing and *CP* Violation (CPV) in the Charm sector
- Search for **direct** *CP* Violation:
  - $D^{\pm} \to K_S^0 K^{\pm}, D_s^{\pm} \to K_S^0 K^{\pm}, D_s^{\pm} \to K_S^0 \pi^{\pm}$ analysis
  - $D^{\pm} \to K^+ K^- \pi^{\pm}$ analysis
- Mixing and search for **indirect** *CP* Violation:
  - $D^0 \to K^+ K^-, \pi^+ \pi^- / D^0 \to K^{\pm} \pi^{\mp}$ lifetime ratio analysis
- Conclusions

Note: all the analyses presented here are **NEW** results not yet submitted for publication and use the full BaBar dataset (**~470 fb^{-1}**)

Flavour Mixing in the Charm Sector

- Mass eigenstates ≠ flavour eigenstates
  $$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

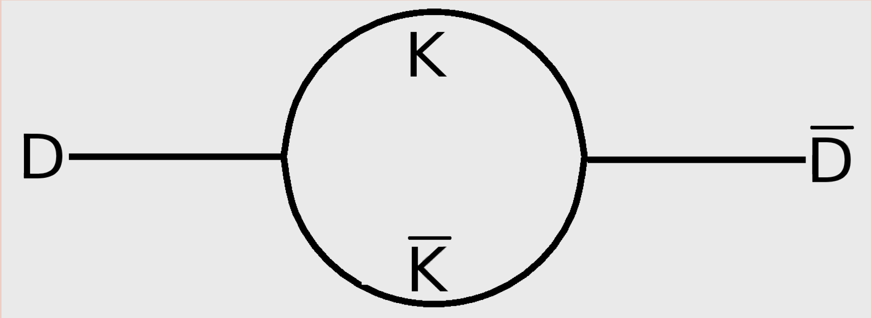
- Definitions: $m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $|D_{1,2}\rangle$ and $\Gamma_D=(\Gamma_1+\Gamma_2)/2$

- **Mixing parameters**

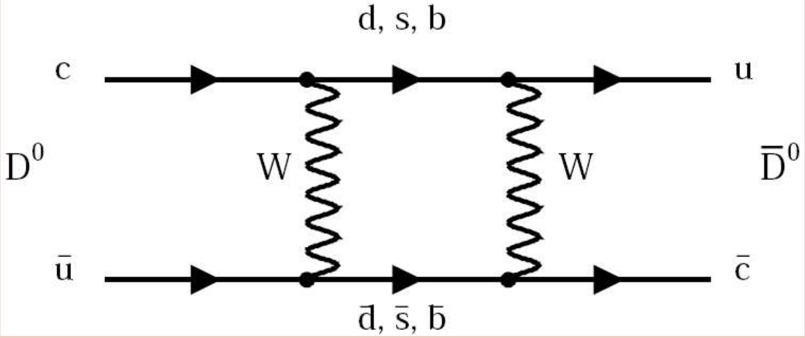
$$x = \frac{m_1 - m_2}{\Gamma_D}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

- Assuming CPT conservation, $|p|^2+|q|^2=1$
- Convention choice: D_1 is CP-even state, CP $|D^0\rangle$ = + $|\overline{D}^0\rangle$

- Long-distance contributions, dominant but affected by large theory uncertainties



- short-distance contributions, GIM and CKM suppressed in SM



CP Violation in the Charm Sector

- Definitions:

$$A_f = \langle D^0|\mathcal{H}|f\rangle \quad A_{\overline{f}} = \langle D^0|\mathcal{H}|\overline{f}\rangle$$
$$\overline{A}_{\overline{f}} = \langle \overline{D}^0|\mathcal{H}|f\rangle \quad \overline{A}_{\overline{f}} = \langle \overline{D}^0|\mathcal{H}|\overline{f}\rangle$$

direct CPV, $A^f_D \neq 0$

$$A^f_D = \frac{|A_f/\overline{A}_f|^2 - |\overline{A}_{\overline{f}}/A_{\overline{f}}|^2}{|A_f/\overline{A}_f|^2 + |\overline{A}_{\overline{f}}/A_{\overline{f}}|^2}$$

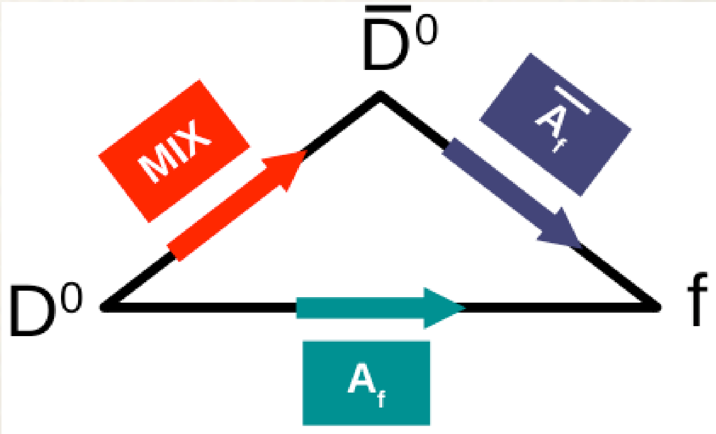
CPV in mixing, $A_M \neq 0$

$$A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}, \quad R_M = \frac{q}{p}$$

CPV in the interference, $\phi_f \neq 0$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\frac{\overline{A}_f}{A_f}\right| \exp[i(\delta_f + \phi_f)]$$

strong +weak phase



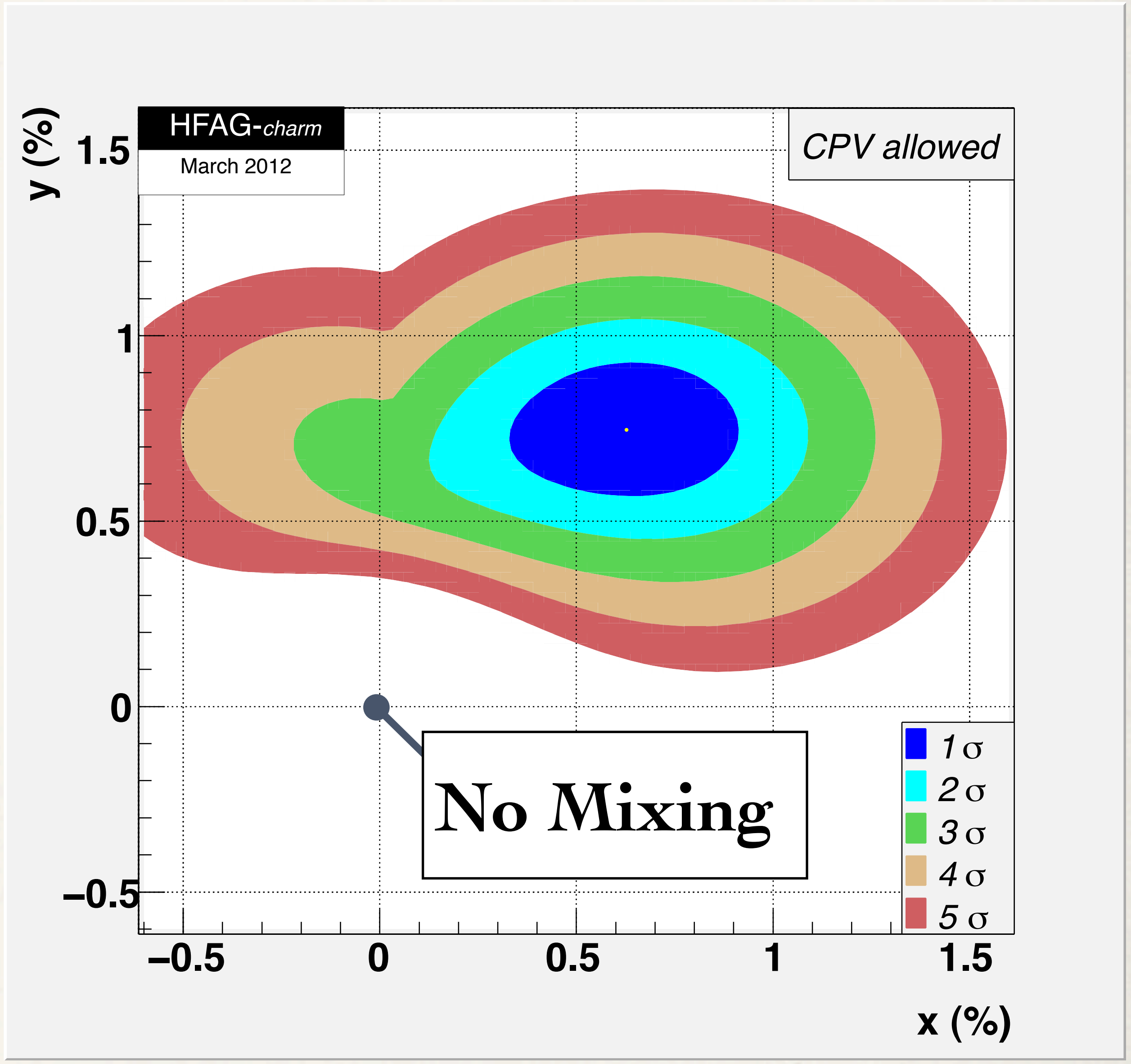
Experimental Status: Mixing

- Mixing in the D_0 system is well established, significance ~10σ

Int.J.Mod.Phys. A21 (2006) 5686-5693

- Standard Model (SM) predictions affected by large uncertainties: x^{theo}, y^{theo} ~ $\mathcal{O}$ (10^{-2}-10^{-7})

- Measurements of x and y are at the upper limit of SM, New Physics (NP) may contribute in short-distance diagrams



http://www.slac.stanford.edu/xorg/hfag/charm/

Experimental Status: CPV

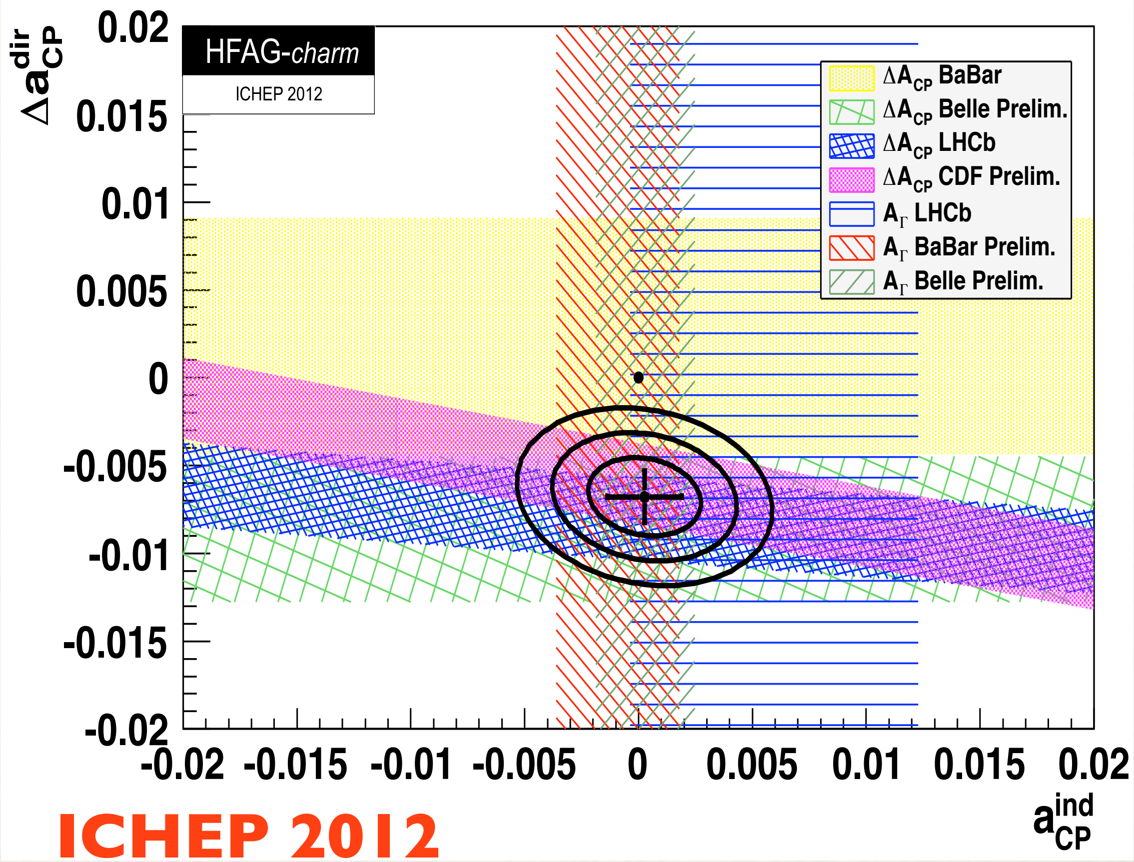
- Recently first evidence of CPV in the charm sector
  - LHCb **PRL 108 (2012) 111602**
  - CDF **arXiv:1207.2158**
- **Combined average exclude CPV at 1.98x10^{-5}**
  - Δa_{CP}(dir)=(-0.678±0.147)%
  - a_{CP}(ind)=(-0.027±0.163)%
- These *CP* asymmetries are marginally compatible with the SM, but uncertainties on the predictions prevent establishing whether this is or not a sign of NP
- CPV in mixing would be a clear sign of NP
- Present experimental goals:
  - Improve precision (also for single asymmetries)
  - Measure single asymmetries in more decay channels

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

$$\Delta A_{\text{CP}} = \left[-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})\right]\%$$

$$\Delta A_{CP} \approx \Delta a_{CP}^{dir}\,(1 + y_{CP}\ \langle t \rangle\ /\tau\,) + a_{CP}^{ind}\,\Delta\ \langle t \rangle\ /\tau$$



http://www.slac.stanford.edu/xorg/hfag/charm/

Searches for Direct CPV

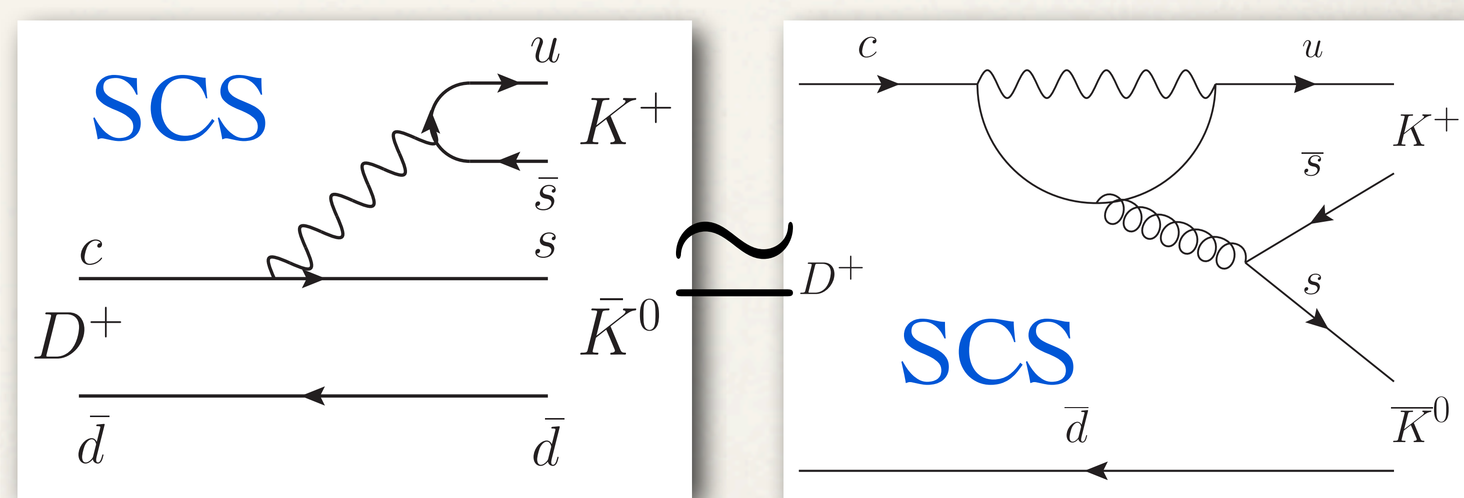
- Need at least 2 amplitudes with different weak and strong phases:
  - Singly Cabibbo Suppressed (SCS): tree + penguin
  - Cabibbo Favoured (CF) + Doubly Cabibbo Suppressed (DCS)
- Time integrated CP asymmetries:

$$A_{CP} = \frac{\mathcal{B}\left(D_{(s)} \to f\right) - \mathcal{B}\left(\overline{D}_{(s)} \to \overline{f}\right)}{\mathcal{B}\left(D_{(s)} \to f\right) + \mathcal{B}\left(\overline{D}_{(s)} \to \overline{f}\right)}$$

- Contribution from $K^0 - \overline{K}^0$ mixing: **+(-)0.332±0.006%** when a K^0 ($\overline{K}^0$) is in the final state
- Three-body decays CPV effects can be enhanced in certain Dalitz Plot (DP) regions
- DP model-dependent and model-independent searches

$D^{\pm} \to K^+K^-\pi^{\pm}$	SCS tree+penguin
$D_s^{\pm} \to K_S^0 K^{\pm}$	CF + DCS
$D^{\pm} \to K_S^0 K^{\pm}$	SCS tree+penguin
$D_s^{\pm} \to K_S^0 \pi^{\pm}$	SCS tree+penguin

$$D^{\pm} \to K_S^0 K^{\pm}$$



$$CPV \sim 0.1\%$$

Searches for Direct CPV

- 3 contributions to the measured value:

$$A_{\rm rec}^{D_{(s)}} = A_{CP}^{D_{(s)}} + A_{FB}^{D_{(s)}}(\cos\theta^*_{D_{(s)}}) + A_\varepsilon^{(\pi,K)}(p^{\rm lab}_{(\pi,K)}, \cos\theta^{\rm lab}_{(\pi,K)})$$

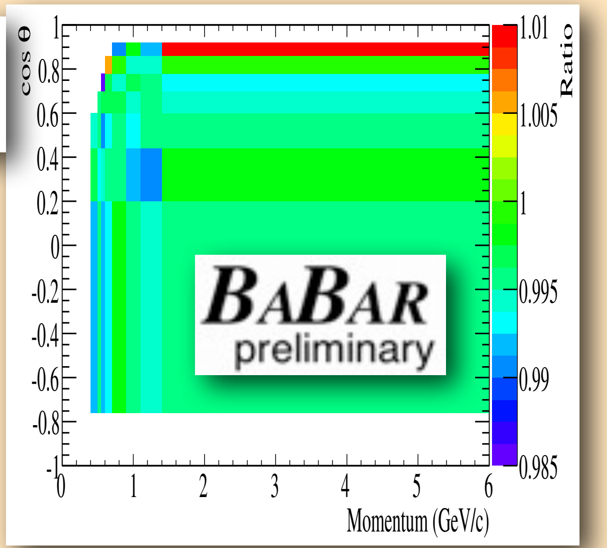
- **Fwd/Bwd asymmetry in $c\bar{c}$ production, A_{FB}**
  - Virtual photon interference with virtual Z^0
  - Odd in cosθ*, used to decouple from A_{CP} (indep. of cosθ*)
  - Additional data-corrected MC only for $D^\pm \to K^+K^-\pi^\pm$

$$A_{CP}(|\cos\theta^*_D|) = \frac{A(+|\cos\theta^*_D|) + A(-|\cos\theta^*_D|)}{2}$$

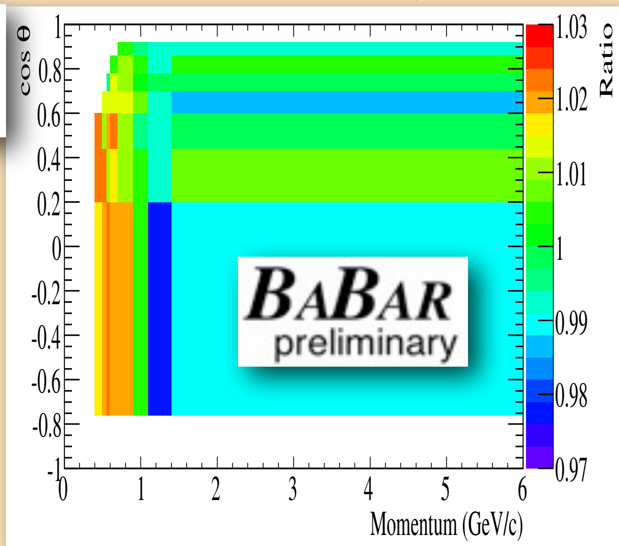
- **Detector-induced charge reconstruction asymmetry:** reconstruction asymm. and material interactions
  - data-driven method ($D^\pm_{(s)} \to K_S h^\pm$)

$$R(p,\cos\theta)_{\rm LAB} = \frac{\varepsilon^+(p,\cos\theta)_{\rm LAB}}{\varepsilon^-(p,\cos\theta)_{\rm LAB}} = \frac{N^+_{\rm rec}(p,\cos\theta)_{\rm LAB}}{N^-_{\rm rec}(p,\cos\theta)_{\rm LAB}}$$

$\pi^\pm$

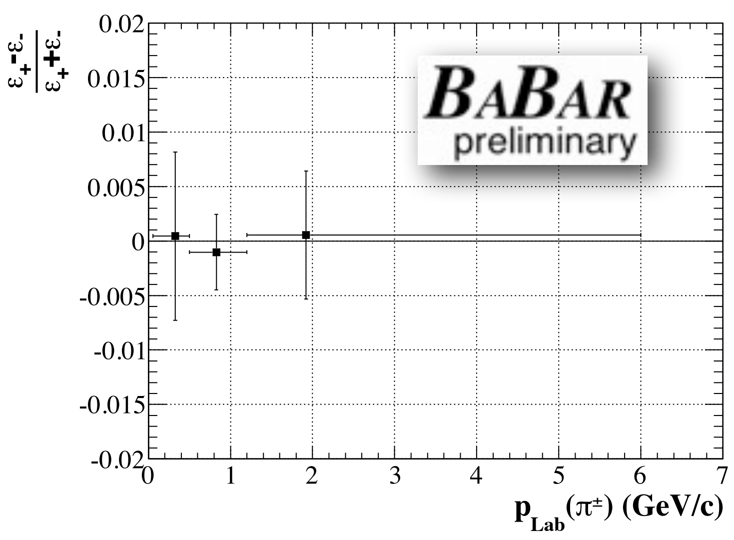


$K^\pm$



- $e^+e^- \to \tau^+\tau^-$ data sample ($D^\pm \to K^+K^-\pi^\pm$)

$$a(p_{Lab}) = \frac{\varepsilon_+(p_\pi) - \varepsilon_-(p_\pi)}{\varepsilon_+(p_\pi) + \varepsilon_-(p_\pi)}$$

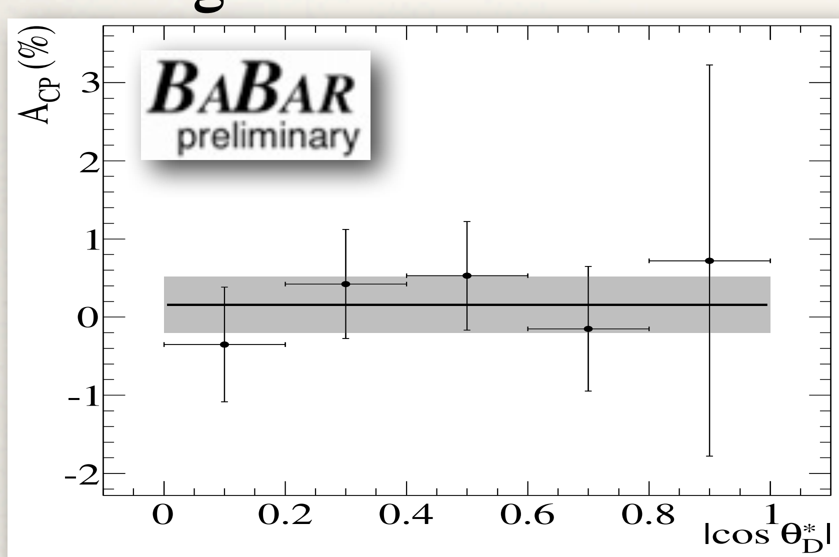


$D^{\pm}\to K_S K^{\pm}$, $D_s^{\pm}\to K_S K^{\pm}$, $D_s^{\pm}\to K_S\pi^{\pm}$ analysis

- Precision goal $O(10^{-3})$, need to keep systematic errors at that level
  - correct for the detector-induced charge reconstruction asymmetry using a data driven method that makes use of physical-asymmetries-free charged track sample from B decays
- Perform simultaneous mass fit and extract the number of $D_{(s)}^{+}$ and $D_{(s)}^{-}$ in 10 bins of $\cos\theta^*$
  - decouple *CP* from FB asymmetry and combine values with a χ^2 fit

$$D^{\pm}\to K^0_S K^{\pm}$$

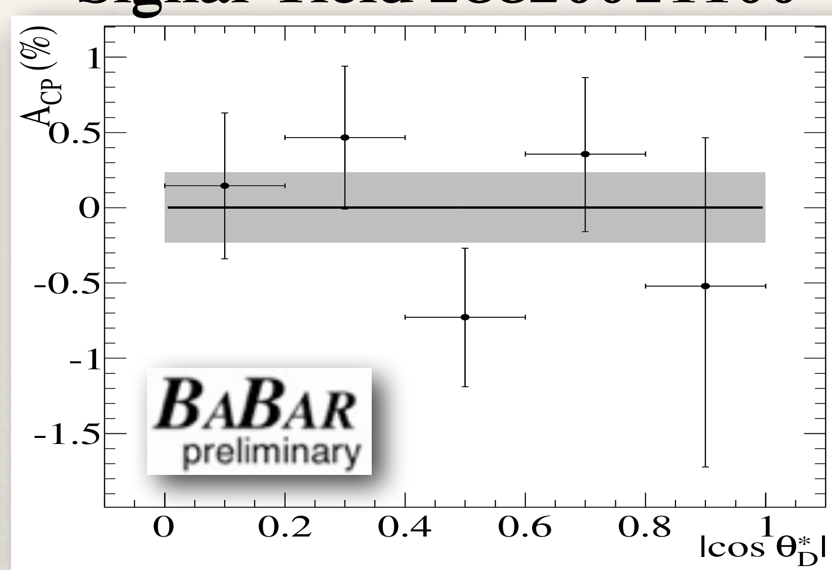
Signal Yield 159400±800



A_{CP} (0.155±0.36)%

$$D_s^{\pm}\to K^0_S K^{\pm}$$

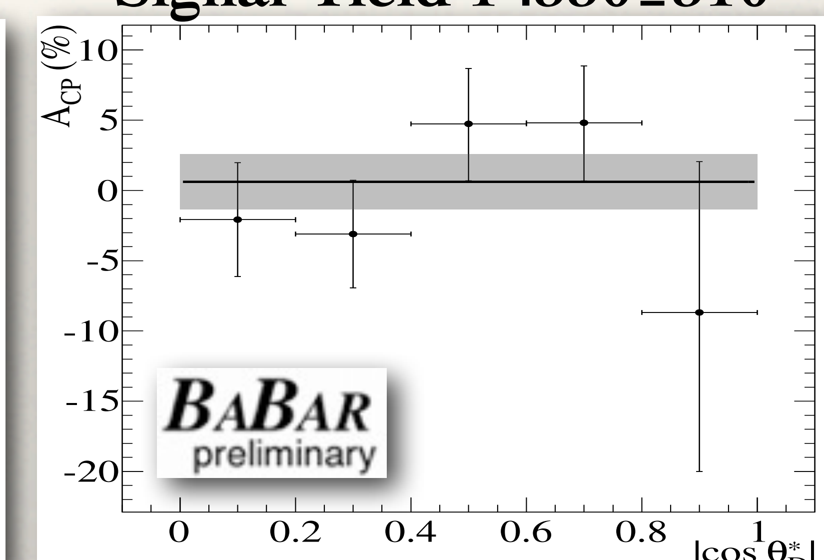
Signal Yield 288200±1100



A_{CP} (0.00±0.23)%

$$D_s^{\pm}\to K^0_S \pi^{\pm}$$

Signal Yield 14330±310



A_{CP} (0.6±2.0)%

$D^{\pm} \to K_S K^{\pm}$, $D_s^{\pm} \to K_S K^{\pm}$, $D_s^{\pm} \to K_S \pi^{\pm}$ results

- Dominant systematic uncertainties:
  - $D^{\pm}_{(s)} \to K_S K^{\pm}$: statistics of the control sample used to correct for the charge asymmetry
  - $D_s^{\pm} \to K_S \pi^{\pm}$: binning in $\cos\theta^*$ to decouple *CP* from FB asymmetry
- Apply corrections and evaluate the contribution of CPV from charm

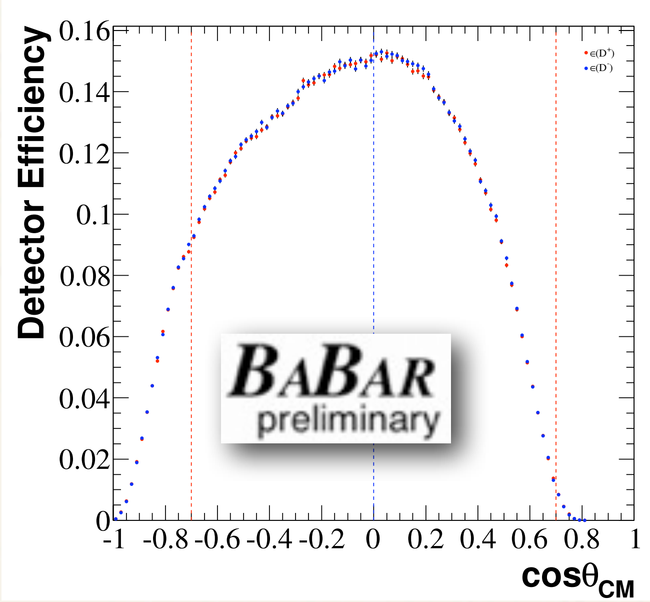
	$D^{\pm} \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S \pi^{\pm}$
A_{CP} value from the fit	$(0.16 \pm 0.36)\%$	$(0.00 \pm 0.23)\%$	$(0.6 \pm 2.0)\%$
Bias Corrections			
Toy MC experiments	$+0.013\%$	-0.01%	$-$
PID selectors	-0.05%	-0.05%	-0.05%
$K^0_S - K^0_L$ interference	$+0.015\%$	$+0.014\%$	-0.008%
A_{CP} corrected value	$(0.13 \pm 0.36 \pm 0.25)\%$	$(-0.05 \pm 0.23 \pm 0.24)\%$	$(0.6 \pm 2.0 \pm 0.3)\%$
A_{CP} contribution from $K^0 - \overline{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(0.332 \pm 0.006)\%$
A_{CP} value (charm only)	$(0.46 \pm 0.36 \pm 0.25)\%$	$(0.28 \pm 0.23 \pm 0.24)\%$	$(0.3 \pm 2.0 \pm 0.3)\%$

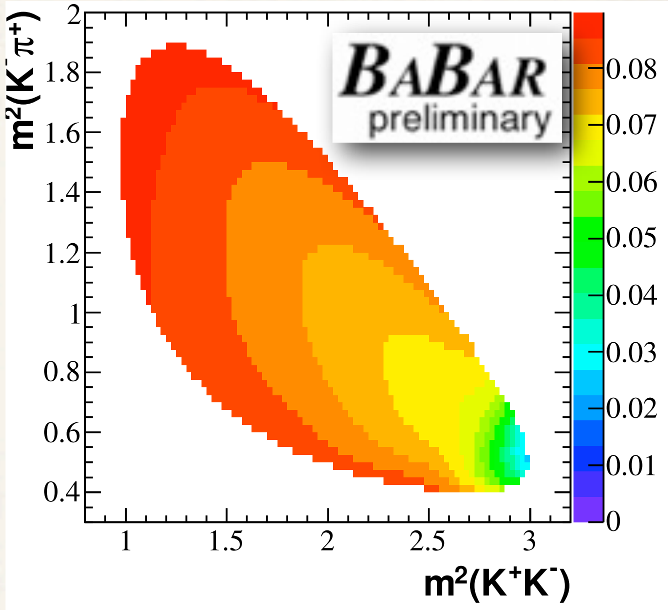
(value)±(stat)±(syst)

No CPV observed

$D^{\pm} \to K^+K^-\pi^{\pm}$, integrated asymmetry

- Efficiency from MC sample generated according uniform phase space
- Parameterizations:
    - cosθ*, to correct for FB asymmetry
    - binned Dalitz plot





- Integrated measurement similar to previous analysis:
    - fit the invariant mass in 8 bins of cosθ*
    - compute the asymmetry in each bin

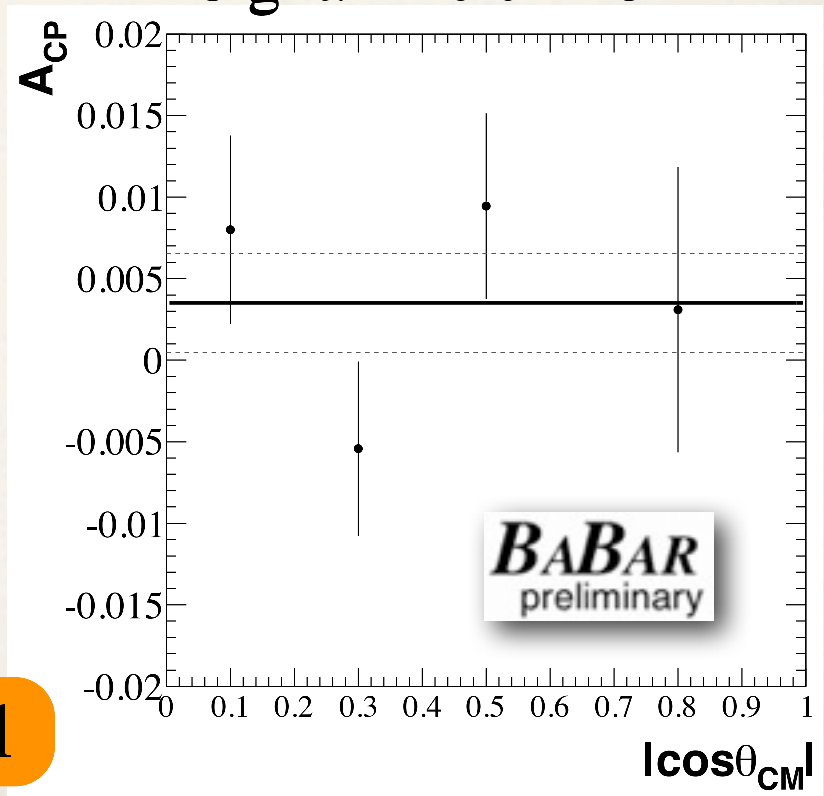
$$A_i \equiv \frac{N_i(D^+)/\varepsilon_i(D^+) - N_i(D^-)/\varepsilon_i(D^-)}{N_i(D^+)/\varepsilon_i(D^+) + N_i(D^-)/\varepsilon_i(D^-)}$$

    - decouple A_{CP} from residual A_{FB} asymmetry combining symmetric bin in cosθ*
    - perform a χ^2 fit to a constant value:

$$A_{CP} = (0.35 \pm 0.30 \pm 0.15)\%$$

No CPV observed

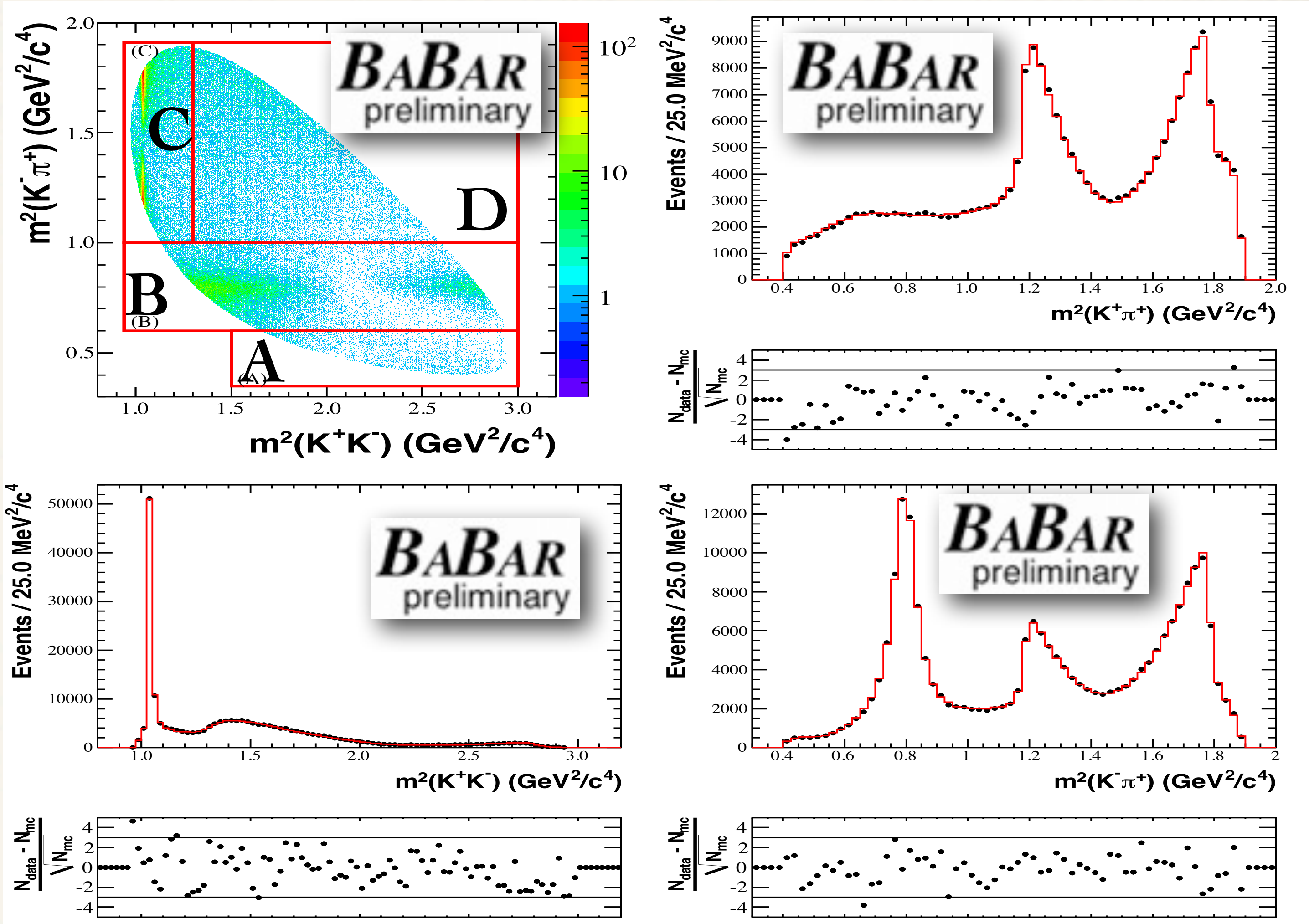
Signal Yield 228k



$D^{\pm}\to K^+K^-\pi^{\pm}$, model independent analysis (1)

- **(1)** Measurement of CP Violation in 4 regions of the DP:
  - divide DP in 4 regions
  - evaluate $N(D^{\pm})$ in each region by fitting the mass distribution
  - correct $N(D^{\pm})$ by the corresponding $\varepsilon(D^{\pm})$, and $N(D^{\pm})$ by R to remove any asymmetry due to physics, like A_{FB}

$$R \equiv \frac{N_{D^+}/\varepsilon_{D^+}}{N_{D^-}/\varepsilon_{D^-}} = 1.020 \pm 0.006$$



Dalitz plot region	$N(D^+)$	$\epsilon(D^+)[\%]$	$N(D^-)$	$\epsilon(D^-)[\%]$	$A_{CP}[\%]$
(A) Below $\bar{K}^*(892)^0$	1882 ± 70	7.00	1859 ± 90	6.97	$-0.65 \pm 1.64 \pm 1.73$
(B) $\bar{K}^*(892)^0$	36770 ± 251	7.53	36262 ± 257	7.53	$-0.28 \pm 0.37 \pm 0.21$
(C) $\phi(1020)$	48856 ± 289	8.57	48009 ± 289	8.54	$-0.26 \pm 0.32 \pm 0.45$
(D) Above $\bar{K}^*(892)^0$ and $\phi(1020)$	25616 ± 244	8.01	24560 ± 242	8.00	$1.05 \pm 0.45 \pm 0.31$

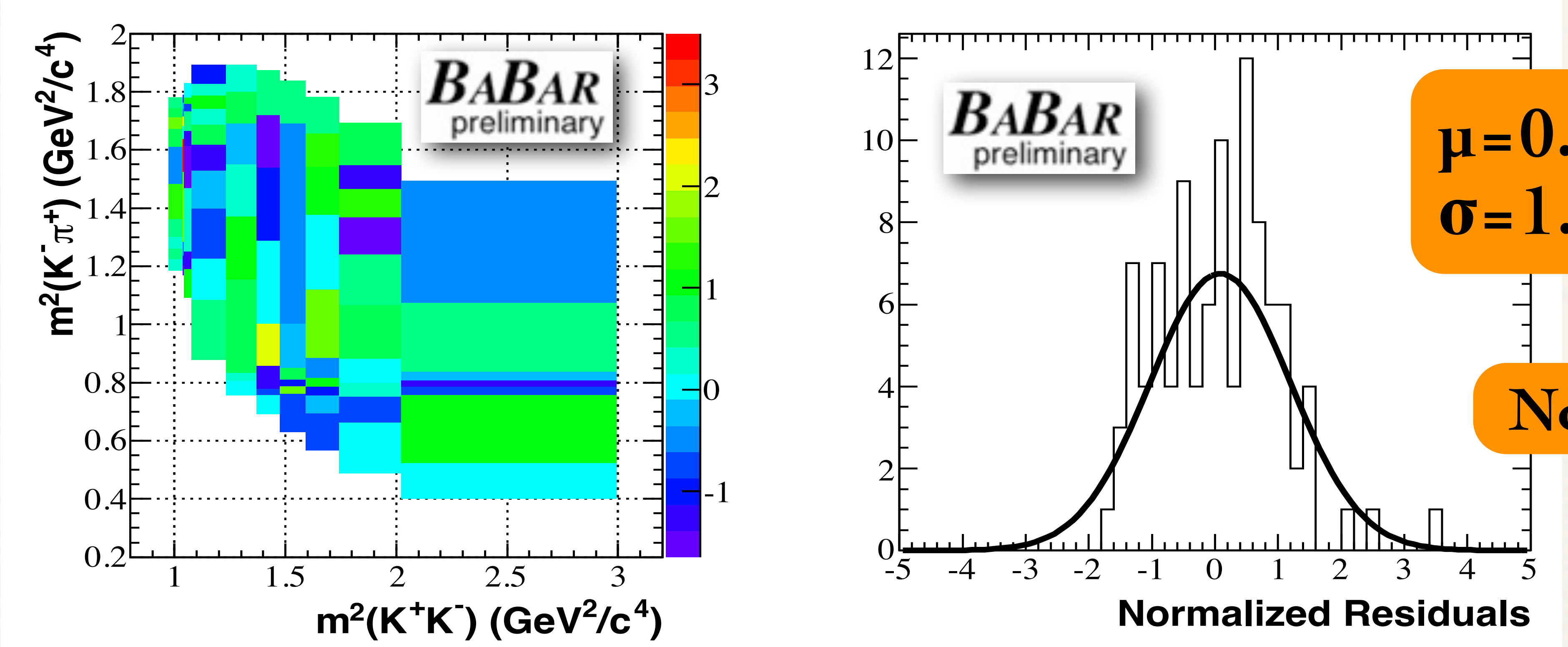
$$A_{CP} \equiv \frac{N(D^+)/\varepsilon(D^+) - R\,N(D^-)/\varepsilon(D^-)}{N(D^+)/\varepsilon(D^+) + R\,N(D^-)/\varepsilon(D^-)}$$

No CPV observed

$D^\pm \to K^+K^-\pi^\pm$, model independent analysis (2)

- **(2)** Normalized residuals of efficiency-corrected and background-subtracted DP for D^+ and D^- computed using an equally populated adaptive binning

$$\Delta_i = \frac{n_i^2(D^+) - Rn_i^2(D^-)}{\sqrt{\sigma_i^2(D^+) + R^2\sigma_i^2(D^-)}}, \quad n_i = \frac{N_i}{\varepsilon_i}$$



μ=0.08±0.15
σ=1.11±0.15

No CPV observed

- **(3)** Legendre polynomial moment analysis **PRD 78, 051102(R) (2008)**
  - Found K^+K^- and $K^-\pi^+$ moments to be consistent with null hypothesis at 11% and 13%, respectively

No CPV observed

$D^{\pm} \to K^+K^-\pi^{\pm}$, model dependent analysis

- Isobar model to describe the DP distribution as a coherent sum of amplitudes
- Each resonance R_i is parameterized with a different amplitude $\mathcal{M}$ and phase ϕ for D^+ and D^- (4 pars.):
- CPV parameters:

$$r = \frac{|\mathcal{M}_i|^2 - |\overline{\mathcal{M}}_i|^2}{|\mathcal{M}_i|^2 + |\overline{\mathcal{M}}_i|^2}$$

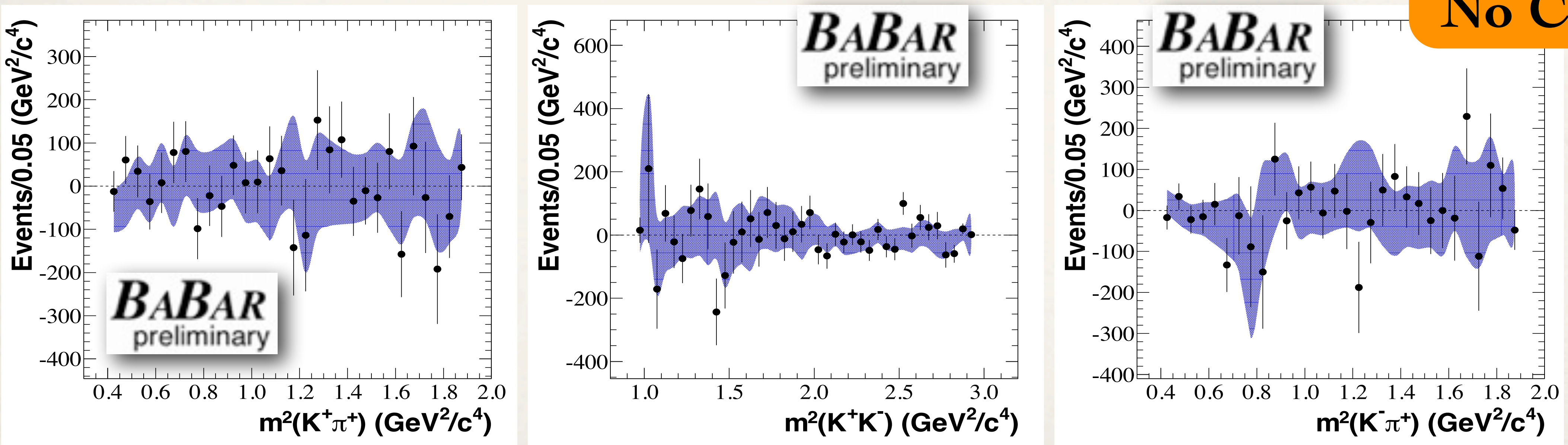
$$\Delta\phi = \phi_i - \overline{\phi}_i$$

  - Cartesian form: Δx and Δy
- Perform a simultaneous fit to the D^+ and D^- DPs

Resonance	r (%)	$\Delta\phi$ (°)
$\bar{K}^*(892)^0$	0. (FIXED)	0. (FIXED)
$\bar{K}_0^*(1430)^0$	$-9.40^{+5.65}_{-5.36} \pm 4.42$	$-6.11^{+3.29}_{-3.24} \pm 1.39$
$\phi(1020)$	$0.35^{+0.82}_{-0.82} \pm 0.60$	$7.43^{+3.55}_{-3.50} \pm 2.35$
NR	$-14.30^{+11.67}_{-12.57} \pm 5.98$	$-2.56^{+7.01}_{-6.17} \pm 8.91$
$\kappa(800)$	$2.00^{+5.09}_{-4.96} \pm 1.85$	$2.10^{+2.42}_{-2.45} \pm 1.01$
$a_0(1450)^0$	$5.07^{+6.86}_{-6.54} \pm 9.39$	$4.00^{+4.04}_{-3.96} \pm 3.83$
	Δx	Δy
$f_0(980)$	$-0.199^{+0.106}_{-0.110} \pm 0.084$	$-0.231^{+0.100}_{-0.105} \pm 0.079$
$f_0(1370)$	$0.019^{+0.049}_{-0.048} \pm 0.022$	$-0.0045^{+0.037}_{-0.039} \pm 0.016$

DP proj: N(D⁺) - N(D⁻) for data (points) and p.d.f (blue curve)

No CPV observed



Mixing and CPV with Lifetime Ratio Analysis

- Simultaneous fit to 5 signal channels:
  - Flavour tagged: $D^{*\pm} \to D^0\pi^\pm$; $D^0 \to K^+K^-, \pi^+\pi^-, K^\pm\pi^\mp$
  - Flavour untagged: $D^0 \to K^+K^-, K^+\pi^-, K^-\pi^+$
- Extract:

Mixing

$$y_{CP} = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} + \frac{1}{\overline{\tau}^+}\right) - 1$$

Indirect CPV

$$\Delta Y = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} - \frac{1}{\overline{\tau}^+}\right)$$

- If no CPV, $y_{CP}=y$ and $\Delta Y=0$
- in general y_{CP} and ΔY depend on the final state

- τ_D = D^0 lifetime ($K^+\pi^-$, $K^-\pi^+$)
- τ^+ ($\overline{\tau}^+$) = D^0 ($\overline{D}^0$) effective lifetime for decays to CP eigenstates (K^+K^-, $\pi^+\pi^-$)

- Experimental assumption:
  - small mixing ($|x|, |y| << 1$) → proper time distributions are exponential with corresponding effective lifetimes to a very good approximation
  - not sensitive to direct CPV and weak phase φ does not depend on final state → KK and ππ modes share common effective lifetimes (crosscheck fit on data)

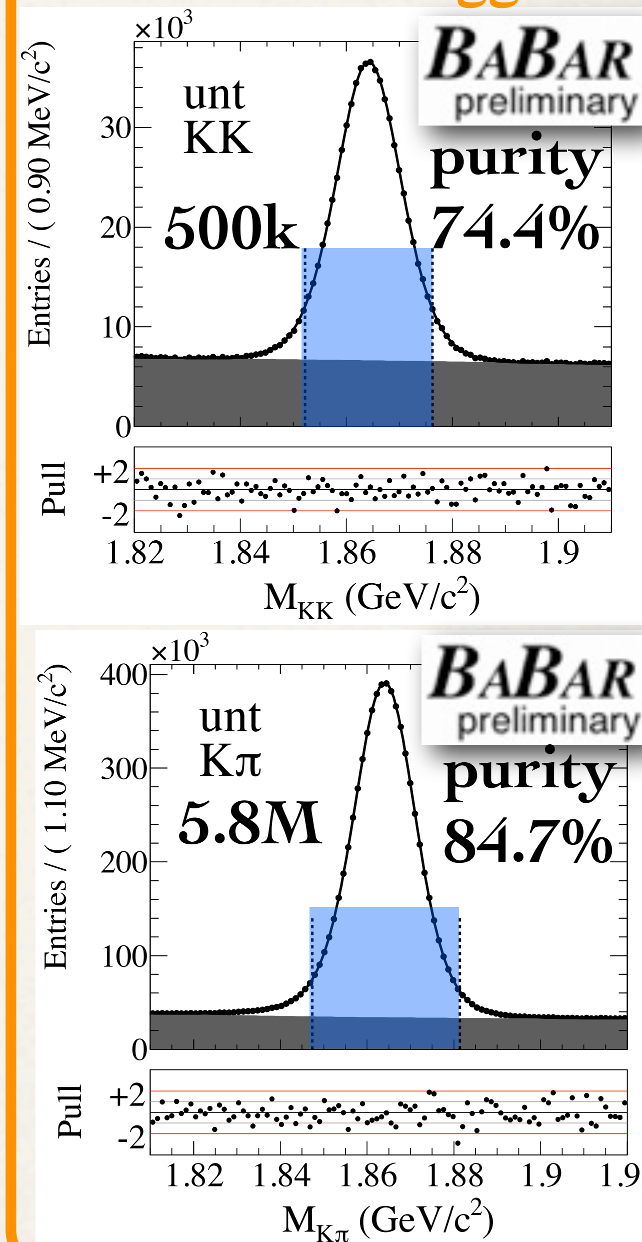
$$y_{CP} = y\cos\phi - \frac{A_M}{2}x\sin\phi$$

$$\Delta Y = -x\sin\phi + \frac{A_M}{2}y\cos\phi$$

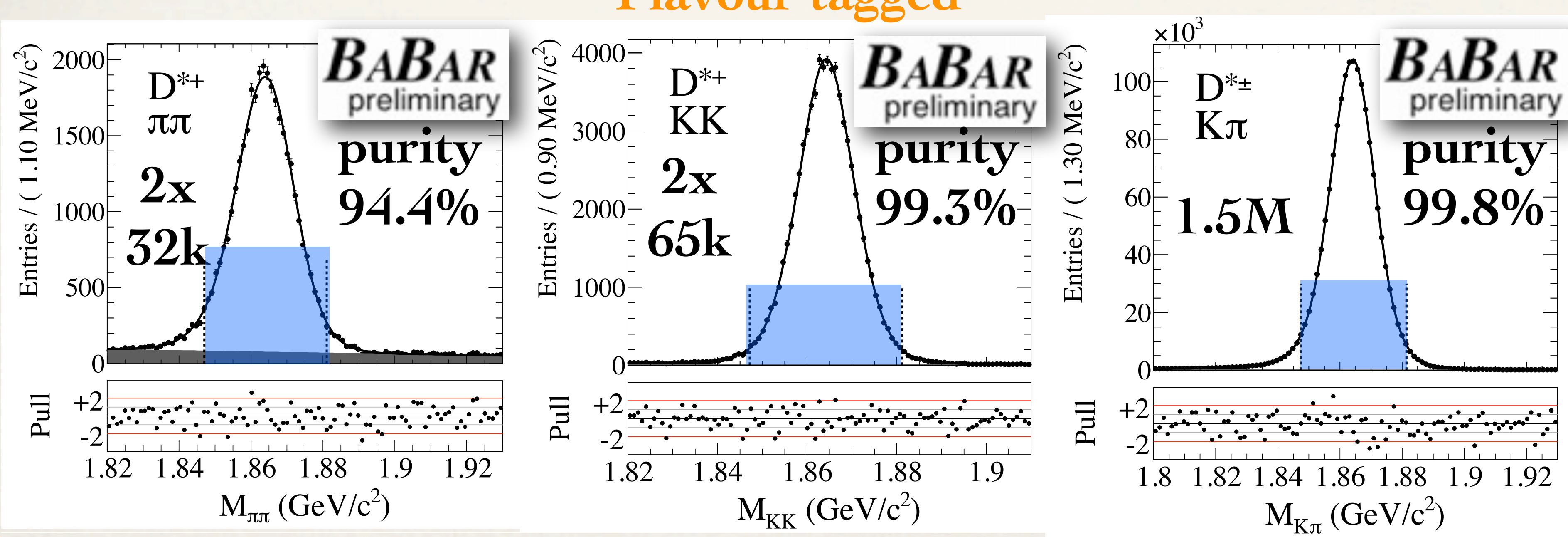
Backgrounds and Data Mass Fits

- **Charm background:**
  - Small component (<0.7%), misreconstructed charm decays, not separated in the mass fit
  - Lifetime fit PDFs and yields are extracted from MC in the signal region
- **Combinatorial background:**
  - Main component, random tracks
  - Lifetime fit PDFs are extracted from data outside the signal region
  - Lifetime fit yields (not for untagged K^+K^-) are extracted from data in the signal region (integral of bkg PDF minus the charm bkg yields from MC)

Flavour untagged



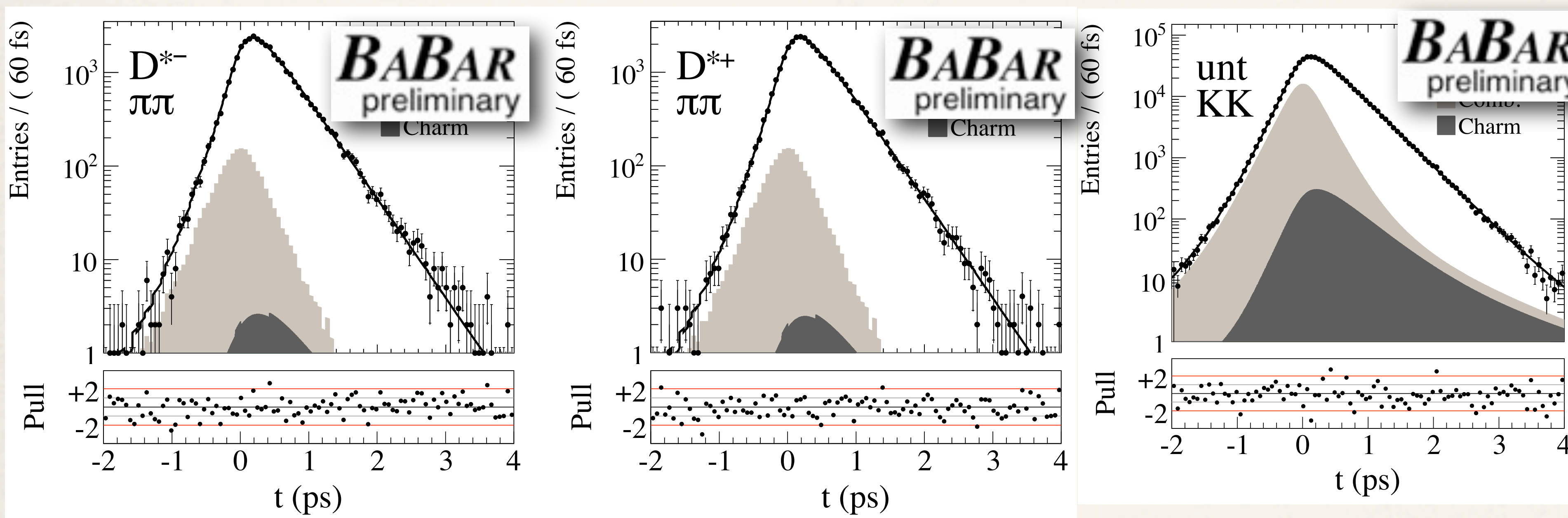
Flavour tagged

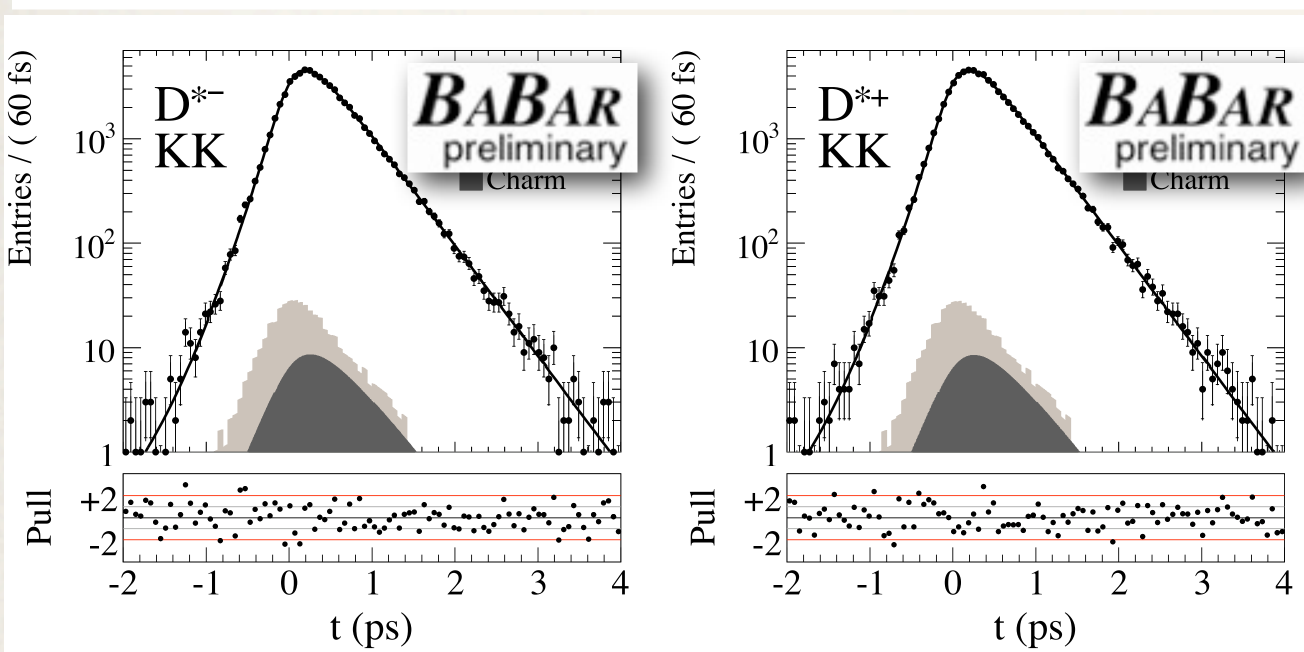


signal region

Proper Time Fit Projections

- Signal: properly normalized 2d conditional PDF (t,σ_t)
- Lifetime 2d fit in the signal region only





- CP+ lifetimes

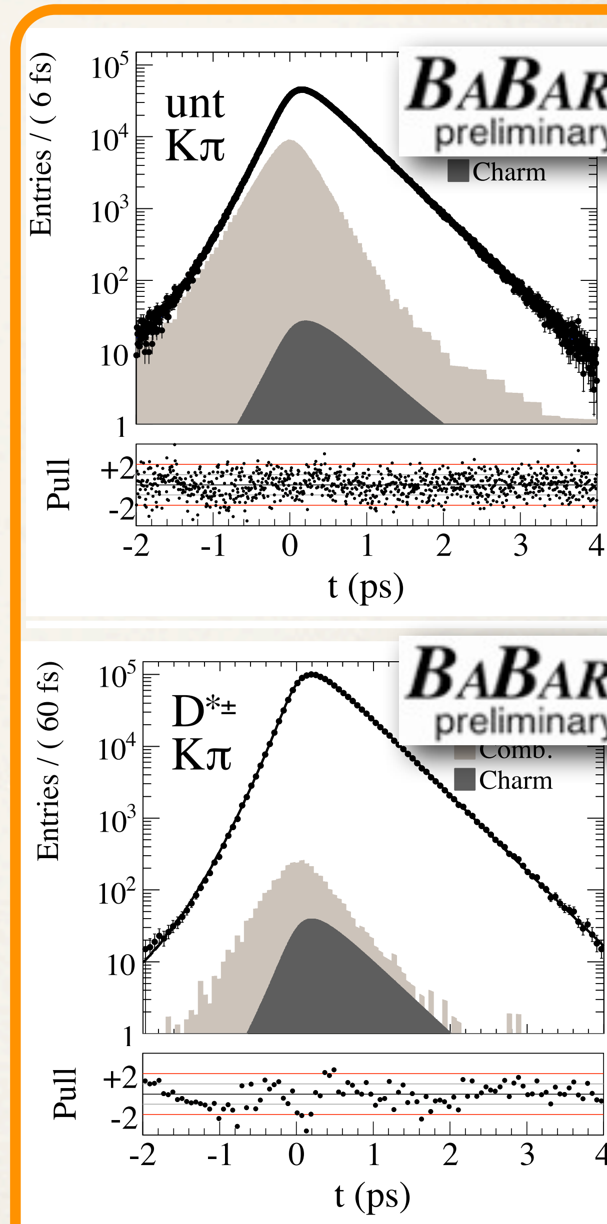
$$\tau^{+} = (405.69 \pm 1.25)\ \text{fs}$$

$$\tau^{-} = (406.40 \pm 1.25)\ \text{fs}$$

- D^0 lifetimes

$$\tau_{K\pi} = (408.97 \pm 0.24)\ \text{fs}$$

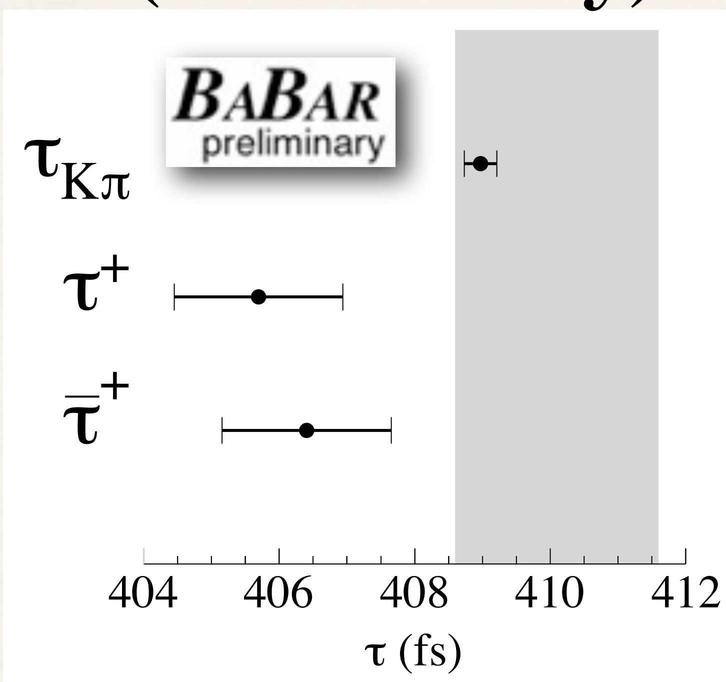
CP+ eigenstates



CP mixed states

Lifetime Fit Results

(stat error only)

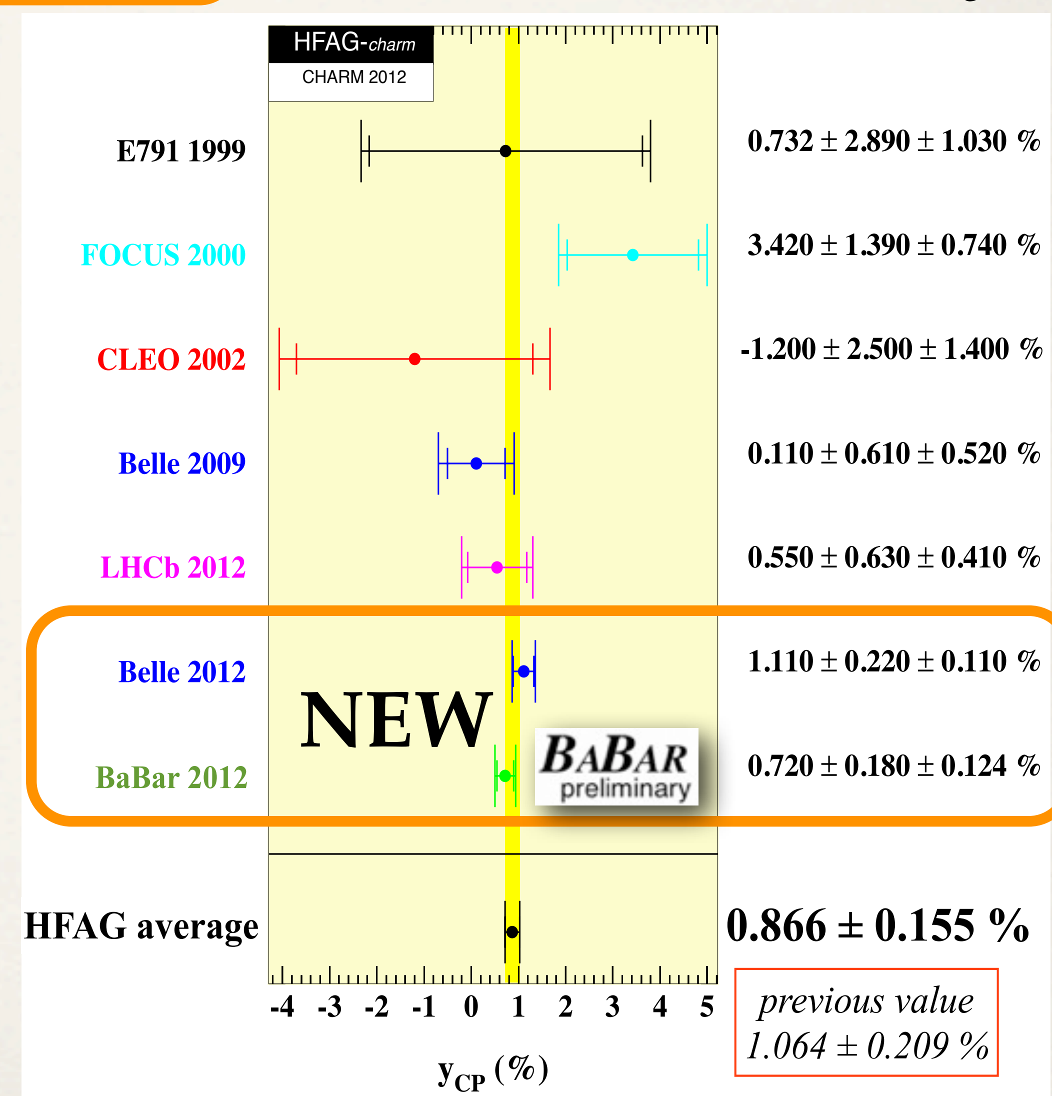


$$y_{CP} = (0.720 \pm 0.180 \pm 0.124)\%$$
$$\Delta Y = (0.088 \pm 0.255 \pm 0.058)\%$$

- Exclude no-mixing @ 3.3σ

No CPV observed

(value)±(stat)±(syst)



- Most precise single measurement of y_{CP}
- Favored y_{CP} value similar to prediction w/o CPV (HFAG value for y=(0.456±0.186)% from direct measurement using $D^0 \rightarrow K_S h^+ h^-$)
- Compatible with previous BaBar results:
  - ΔY=(-0.26±0.36±0.08)% **PRD 78, 011105 (2008)** **(Opposite sign definition)**
  - y_{CP} =(1.16±0.22±0.18)% **PRD 80, 071103 (2009)**
- This result supersedes the previous BaBar results

Conclusions

- Increase in precision and inclusion of more channels are needed to understand the origin of the *CP* violation reported by LHCb and CDF
- We have searched for *CP*-violating effects with the full BaBar data sample reaching a precision down to $O(10^{-3})$
- We have found **NO** evidence of direct or indirect CP violation in the following channels:
  - $D^{\pm} \rightarrow K_S K^{\pm}$, $D_s \rightarrow K_S K^{\pm}$, $D_s \rightarrow K_S \pi^{\pm}$ (direct CPV)
  - $D^{\pm} \rightarrow K^{+} K^{-} \pi^{\pm}$ (direct CPV)
  - $D^0 \rightarrow K^{+} K^{-}$, $D^0 \rightarrow \pi^{+} \pi^{-}$ (indirect CPV)
- We have measured y_{CP} with the highest precision to date, and excluded the no-mixing hypothesis at 3.3σ significance

Systematics: $D^{\pm}\to K_S K^{\pm}$, $D_s^{\pm}\to K_S K^{\pm}$, $D_s^{\pm}\to K_S \pi^{\pm}$

- Dominant contributions:
  - control sample statistics for correction of detector-induced asymmetry
  - binning choice

Syst. uncertainty (absolute)	$D^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 \pi^{\pm}$
Efficiency of PID selectors	0.05%		0.05%
Statistics of control sample	0.23%		0.06%
Selection of control sample	0.01%		0.01%
$\cos\Theta^*$ binning	0.04%	0.02%	0.27%
K^0-$\overline{K}^0$ regeneration [1]	0.05%	0.05%	0.06%
K_S^0-K_L^0 interference [2]	0.015%	0.014%	0.008%
Total	0.25%	0.24%	0.29%

[1] arxiv:1006.1938
[2] arXiv:1110.3790v1

Systematics: lifetime fit

Fit Variation	$\lvert\Delta[y_{CP}]\rvert$ (%)	$\lvert\Delta[\Delta Y]\rvert$ (%)
mass window width	0.057	0.022
mass window position	0.005	0.001
untagged KK signal σ_t PDF	0.022	0.000
mistag fraction	0.000	0.000
untagged KK D^0 fraction	0.001	0.000
charm bkgd. lifetimes	0.042	0.001
charm bkgd. yields	0.016	0.000
comb. yields	0.043	0.002
comb. sideband weights	0.004	0.001
comb. PDF shape	0.066	0.000
σ_t selection	0.052	0.053
candidate selection	0.028	0.011
Total	0.124	0.058